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Attribution of anthropogenic influence on seasonal sea level pressure

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[1] Previous analyses of sea level pressure (SLP) trends have often focused on boreal winter trends. Here we demonstrate that externally-forced SLP trends are observed in all four seasons, with simulated and observed decreases in SLP at high latitudes and increases elsewhere. We find that the observed pattern of seasonal mean zonal mean SLP changes is inconsistent with simulated internal variability, and we detect anthropogenic influence independently of natural influence on SLP. When we divide the globe into the mid- and high-latitude regions of both hemispheres and the tropics and subtropics, we find that external influence is only detectable in the low-latitude region, where models and observations show increasing trends in SLP, and where internal variability is low, and not in the mid- and high-latitude regions of either hemisphere. Low-latitude increases in SLP, which are significant compared to internal variability, but which have previously received little attention, could have important regional climate impacts. **Citation:** Gillett, N. P., and P. A. Stott (2009), Attribution of anthropogenic influence on seasonal sea level pressure, *Geophys. Res. Lett.*, *36*, L23709, doi:10.1029/2009GL041269.

1. Introduction

[2] Previous work on sea level pressure changes has often focused on the boreal winter season, when the largest trends have been observed. In this season, sea level pressure has decreased over the Arctic, Antarctic and North Pacific, and has increased over the subtropical North Atlantic, southern Europe and North Africa [e.g., *Trenberth et al.*, 2007]. These changes have often been characterised as a shift towards the positive phase of the Northern Annular Mode (NAM) and Southern Annular Mode (SAM) [*Thompson et al.*, 2000; *Trenberth et al.*, 2007], with most attention focused on the larger high latitude changes. Global sea level pressure changes in December–February (DJF) have been shown to be inconsistent with simulated internal variability [*Gillett et al.*, 2003, 2005; *Wang et al.*, 2009]. Other studies have also concluded that observed trends in DJF are inconsistent with simulated internal variability in the NAM [*Osborn*, 2004; *Gillett*, 2005] and SAM [*Marshall et al.*, 2004]. However, the trend in the NAM has generally been found to be larger than that simulated [*Osborn*, 2004; *Gillett*, 2005; *Miller et al.*, 2006]. While natural forcing is not expected to be a strong driver of SLP trends over recent decades, none of the previously-mentioned attribution studies of SLP were able to separate anthropogenic and natural influence on SLP in a multiple regression, thus none of them formally attributed SLP changes to anthropogenic influence [*Hegerl et al.*, 2007].

[3] While most studies of SLP trends have focused on DJF, some studies have examined trends in other seasons. *Wang et al.* [2009] attempted to detect external influence on global HadSLP2 SLP trends in each of the four seasons separately, but did not find detectable external influence on SLP in any season, although they did find detectable external influence in SLP gradients in JFM and JAS. *Marshall et al.* [2004] examined trends in a station-based SAM index over the period 1965–1997, and found the largest positive trend in DJF, consistent with simulations of HadCM3 including greenhouse gas increases, stratospheric ozone depletion, and natural climate influences. The next strongest trends were simulated and observed in MAM, with JJA and SON both showing weak positive SAM trends in the model and observations. In this study, we examine SLP trends in all four seasons, and apply an attribution analysis to test for the presence of anthropogenic and natural influence in a multiple regression. Both the NAM and the SAM indices peaked in the late 1990s and have since declined somewhat [*Hegerl et al.*, 2007] - we therefore also test whether anthropogenic influence is detectable in data up to the present.

2. Data and Model

[4] We use the HadSLP2.0 uninterpolated gridded SLP observations for the period 1850–2004, and HadSLP2r to update the dataset to February 2009 [*Allan and Ansell*, 2006]. We compare observed trends with simulations of HadGEM1 [*Johns et al.*, 2006; *Stott et al.*, 2006], an atmosphere model with resolution 1.25° × 1.875° and 39 levels, coupled to a dynamical ocean model. We consider three ensembles of simulations: A three-member ensemble with observed well-mixed greenhouse gas changes only (GHG), a four-member ensemble which also includes land-use change, sulphate aerosol, carbonaceous aerosol, tropospheric ozone, and stratospheric ozone changes (ANT), and a four-member ensemble which in addition includes volcanic aerosol and solar irradiance changes (ALL). All simulations were started in December 1859 and continued at least until the end of 2009 (most CMIP3 simulations finished in 2000 or earlier, therefore our analysis is restricted to a single model). Simulations were extended beyond 2000 using SRES A1B anthropogenic forcings, assuming an exponential decay of volcanic aerosol remaining in the stratosphere in 2000 with a timescale of one year, and an 11-yr solar cycle with an amplitude of the average of the two previous cycles. To assess internal variability we use a 910-year control simulation. Five-year mean seasonal mean SLP from the model was interpolated onto the observational grid, and sampled in grid cells with

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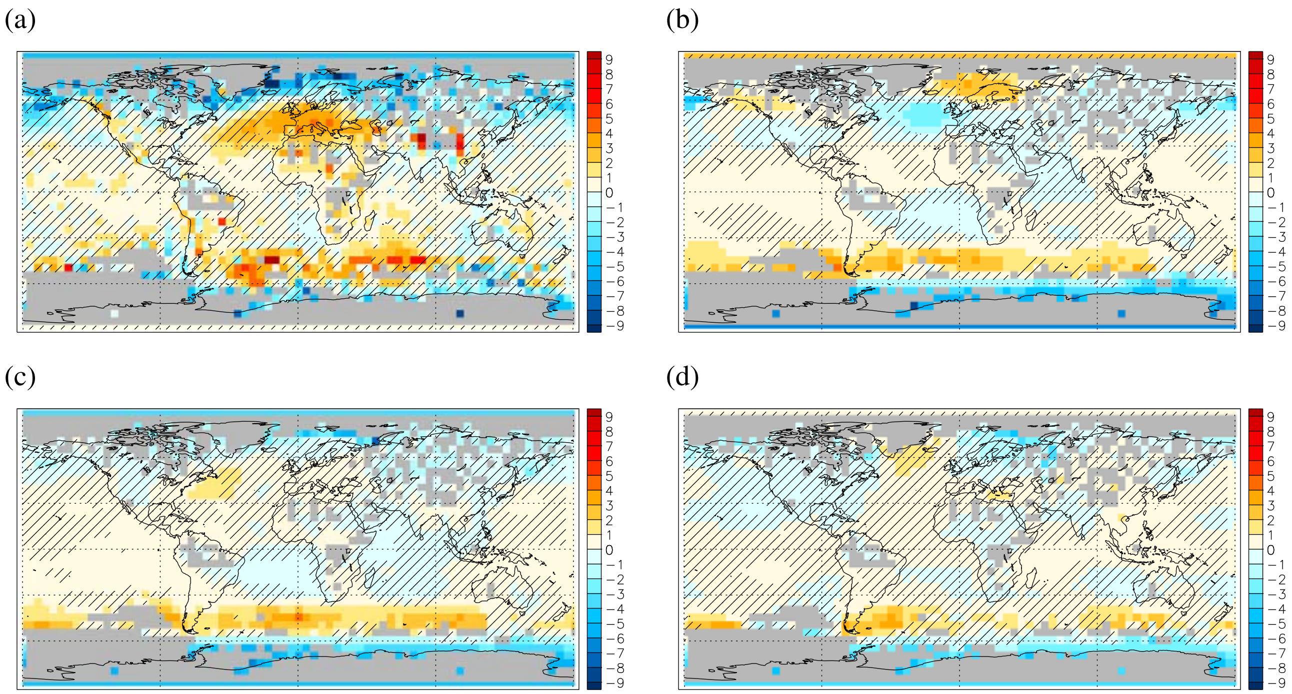

Figure 1. Linear trends in DJF sea level pressure based on 5-yr means between 1949 and 2009 in (a) HadSLP2, (b) HadGEM1 simulations with anthropogenic and natural forcings (ALL), (c) HadGEM1 simulations with anthropogenic forcings only (ANT), and (d) HadGEM1 simulations with greenhouse gas forcing only (GHG) (hPa/60 yr). Regions with trends not significant at the 5% level, based on simulated internal variability, are hatched.

observations, where at least 50% of monthly values were required to calculate a 5-yr mean.

3. Results

[5] Figure 1a shows DJF sea level pressure trends at each grid cell with at least 50% of 5-yr means present over the period 1949–2009 (similar maps for the other seasons are shown in Figures S1–S3 of the auxiliary material).[1] As expected, these are similar to the trends presented by *Gillett et al.* [2005] based on the same dataset over the period 1955–2005, showing decreases over both polar regions, and increases over the southern midlatitudes, subtropical North Atlantic, southern Europe and North Africa. Note that the large increases seen over the high topography of the Tibetan Plateau may be spurious (R. Allan, personal communication, 2009). We prefer to restrict attention to observed locations, and avoid comparing with reanalyses which are known to exhibit spurious SLP trends [e.g., *Marshall*, 2003]. Figures 1b–1d show simulated trends in the ALL, ANT and GHG ensembles of HadGEM1 respectively. The ALL trends shown in Figure 1b are broadly consistent with the mean simulated response in eight CMIP3 models incorporating similar anthropogenic and natural forcings [*Gillett et al.*, 2005], although the increasing SLP trend simulated over Scandinavia and the Norwegian Sea is particular to the ALL simulations of HadGEM1. Similar SLP trends are simulated in the ANT ensemble (Figure 1c). The GHG ensemble also shows negative trends in SLP over the Antarctic and positive trends in the southern midlatitudes, albeit of a smaller magnitude than those in ANT and ALL, because of the absence of ozone depletion (Figure 2). The observations show generally positive but weak increases in SLP in the tropics and subtropics of both hemispheres, and the same thing is seen in the ANT and ALL ensembles, although the increases observed over the Mediterranean region are not reproduced by the model.

[6] In order to focus attention on the most robust large-scale aspects of the SLP response subsequent analysis was performed using zonal mean SLP, calculated over seven 25° zonal bands between 87.5°N and 87.5°S using area weighting and sampling model output where observations are present. Figure 2 shows trends in zonal mean SLP for all four seasons in the observations and in HadGEM1. Grey bands show the 11th and 207th largest trends (approximate 5th and 95th percentiles) in 217 overlapping 60-yr control segments. Thus the grey bands may be used to assess the local significance of the observed trends. The simulated ALL trends have half the sampling uncertainty associated with the observed trends, since they are four-member ensemble means, thus they may be significant even when within the grey bands. The broader grey bands at high latitudes compared to the tropics reflect a real difference in SLP variability, as well as more limited sampling at high latitudes, particularly in the Southern Hemisphere (Figure S4). The largest trends are observed in DJF at almost all latitudes, with decreases in SLP at high latitudes and increases elsewhere. However a similar signal is found in the other seasons, albeit with weaker amplitude. The SLP trends are largest in the high latitudes of the Northern Hemisphere, particularly in DJF, but internal variability is also larger there. Persistent positive trends are observed in the tropics, subtropics and southern midlatitudes: For

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL041269.

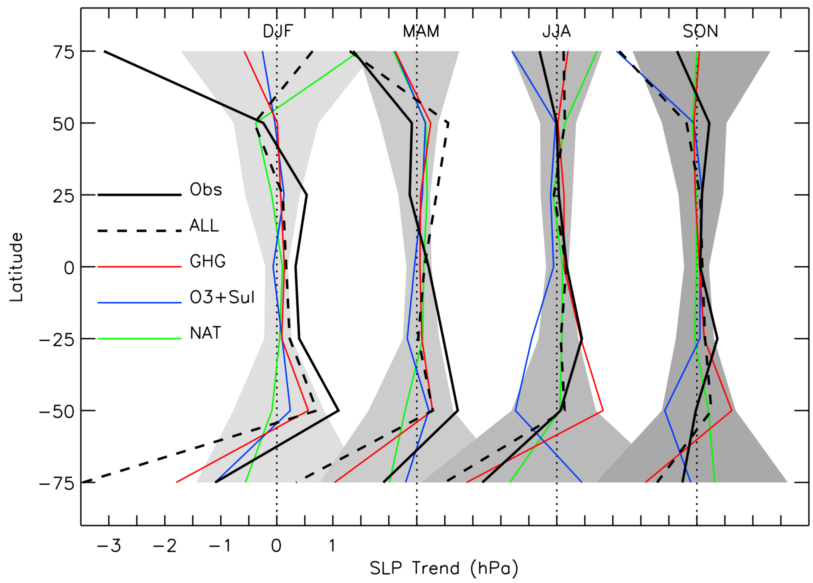

Figure 2. Trends in seasonal mean sea level pressure in seven 25°-latitude bands between 87.5°S and 87.5°N calculated from 5-yr means over the period December 1949–November 2009. Observed trends from HadSLP2 (solid black) are compared to trends simulated in response to greenhouse gases (red), ozone and sulphate aerosol (blue), natural forcings (green), and all forcings (dashed black) in HadGEM1. The simulated ozone and sulphate response is the difference between the ANT and GHG simulated trends, and the natural response is the difference between the ALL and ANT simulated trends. Grey bands represent the approximate 5%–95% range of simulated SLP trends in 910 years of control simulation of HadGEM1 (hPa/60 yr).

example the band centred at 25°S shows a significant positive trend in every season.

[7] The simulated and observed patterns of zonal mean trends are broadly consistent, with the ALL simulations reproducing negative trends at 75°S, and at 75°N in SON and MAM, and some increases at lower latitudes. The only discrepancies significant at the 5% level are in DJF, where the observed SLP trend at 75°N is strongly negative, whereas the simulated trend is weakly positive - this difference is dominated by differences in the simulated and observed trends over the North Atlantic north of 60°N (Figure 1), and at 75°S, where the simulated trend is larger than that observed. The similarity of the simulated and observed trends in the seasons other than DJF suggests that SLP from these seasons may contribute extra useful information in an attribution analysis.

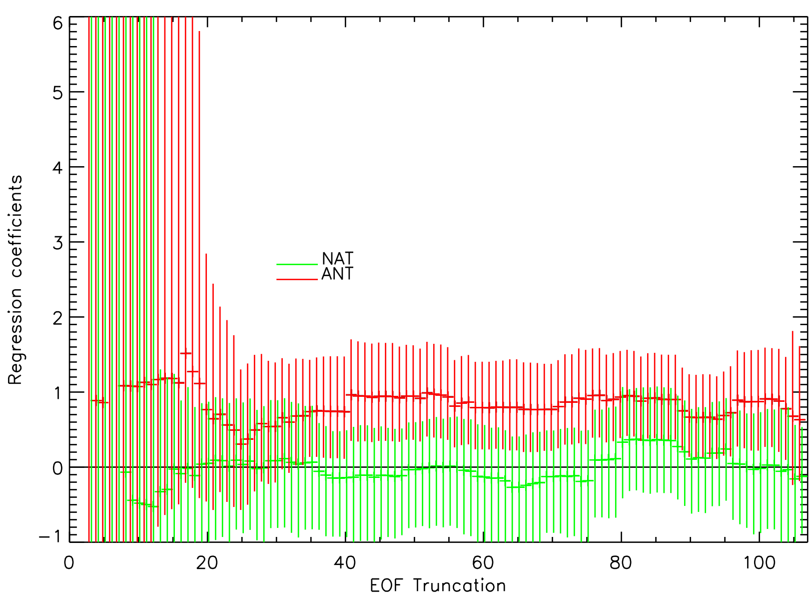

Figure 3. Regression coefficients of observed SLP changes onto the simulated anthropogenic (ANT) and natural (NAT) responses in a multiple regression, plotted as a function of EOF truncation. Lines show 5–95% uncertainty ranges. Results are based on 5-yr mean seasonal mean zonal mean SLP in seven 25°-latitude bands between December 1949 and November 2009, from an analysis using data from all four seasons simultaneously.

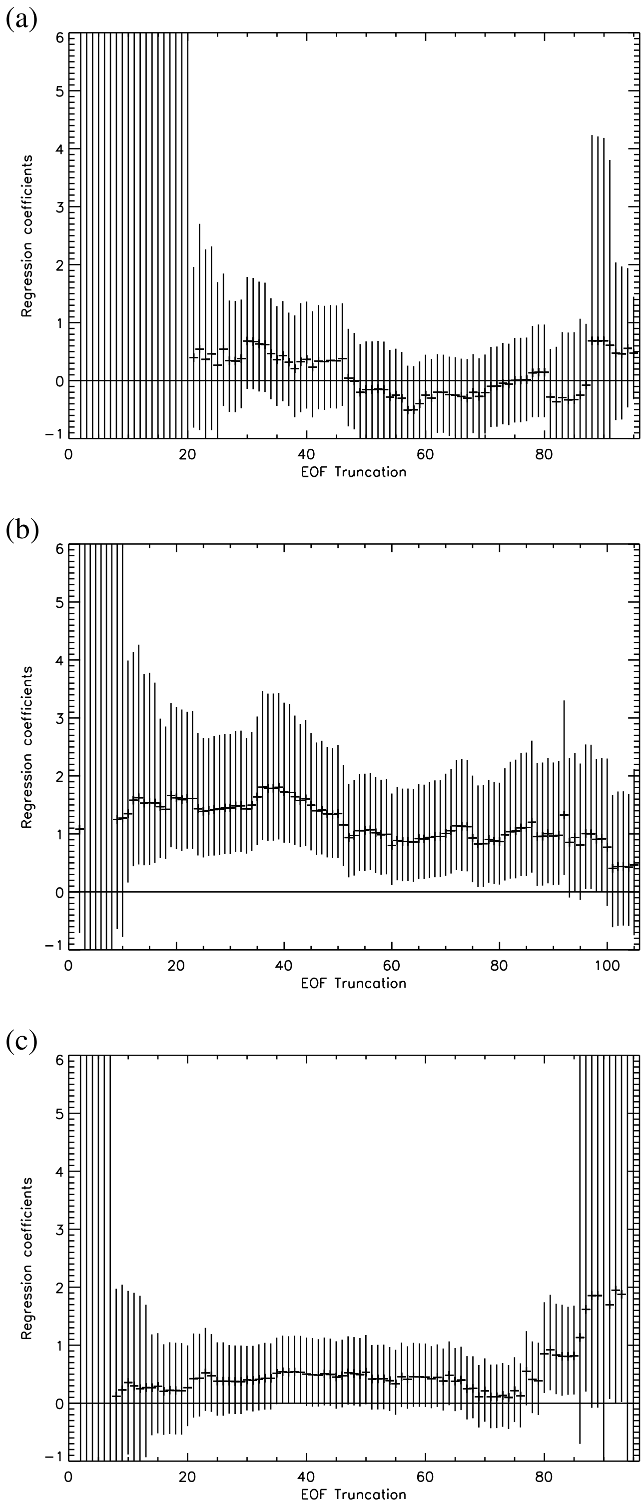

Figure 4. Regression coefficients of observed SLP changes onto the simulated response to combined anthropogenic and natural forcing (ALL), plotted as a function of EOF truncation, for (a) the region north of 37.5°N, (b) the region between 37.5°N and 37.5°S, and (c) the region south of 37.5°S.

[8] We applied an attribution analysis to test for the presence of an externally-forced response using information from all latitude bands and seasons. Observed 5-yr mean zonal mean SLP from 1949–2009 and in seven latitude bands was regressed onto the same diagnostic evaluated from the ALL and ANT ensembles of HadGEM1 using a total least squares analysis [*Allen and Stott*, 2003]. We used 5-yr means of SLP rather than trends in the expectation that any natural signal might be better resolved by this diagnostic. Before performing the regression, the simulated and observed data were projected onto a varying number of the leading EOFs of simulated internal variability, evaluated from the first half of the available 910 years of control simulation. Uncertainties on the regression coefficients were evaluated using the latter half of the 910-yr control simulation. The output regression coefficients for ALL and ANT were transformed into separate regression coefficients for the anthropogenic (ANT) and natural (NAT) responses [*Allen and Tett*, 1999]. The resulting regression coefficients are shown as a function of EOF truncation in Figure 3. The ANT regression coefficients are inconsistent with zero for a broad range of truncations from 35 to 104, indicating that an anthropogenic response is detectable independently of the natural response. Perhaps owing to the large size of the data vector used (12 5-yr means, 7 latitude bands, and 4 seasons), a relatively high EOF-truncation is required to distinguish the ANT regression coefficient from zero. However, a residual test [*Allen and Tett*, 1999] did not indicate any evidence of underestimated internal variability at any of the truncations plotted: if anything residual variability was smaller than simulated internal variability, thus results at these truncations should be considered reliable. The ANT regression coefficient was also consistent with one in all cases in which an anthropogenic response was detected, indicating consistency between the magnitude of the simulated and observed response. A response to natural forcing was not detectable.

[9] We tested which region contributes the most to the detectability of external forcing on SLP by repeating the analysis performed globally for the region north of 37.5°N, for the region between 37.5°N and 37.5°S, and for the region south of 37.5°S. The anthropogenic response was not detectable independently of the natural response in a two-pattern multiple regression [*Allen and Stott*, 2003], therefore we restrict our attention to the detection of the ALL response in a single-pattern regression. Figure 4 shows that a response to external forcing is robustly detectable in the subtropics and tropics, but is not robustly detectable in the mid- and high-latitude region of either hemisphere. Even though the magnitude of the simulated and observed trends is generally larger at high latitudes, the internal variability is also much larger, and therefore the signal-to-noise ratio is higher for the tropics and subtropics (Figure S5).

4. Discussion and Conclusions

[10] The pattern of decreases in SLP in the high latitudes of both hemispheres and increases elsewhere which has been observed in DJF persists through all four seasons, albeit with weaker magnitude. This pattern of trends remains robust when calculated using data up to 2009. Anthropogenic influence is detectable independently of

natural influence using zonal mean seasonal mean SLP data, based on simulations of HadGEM1 including greenhouse gases, sulphate aerosol, stratospheric ozone depletion and natural climate influences, and another set of simulations with natural influences alone. No sets of simulations up to 2009 with separate natural and anthropogenic forcings are available from other models: Once they become available it would be desirable to use them to verify the robustness of our results. On the global scale, the magnitude of simulated and observed zonal mean SLP trends is found to be consistent, unlike previous analyses which either focused on the NAM or NAO [e.g., *Gillett*, 2005], or comparisons with simulations which excluded the effects of stratospheric ozone depletion [*Gillett et al.*, 2003].

[11] While most attention in the past has focused on the relatively large high-latitude decreases in SLP [e.g., *Hegerl et al.*, 2007], we find that when we consider the mid- and high-latitude regions and the tropics and subtropics separately, external influence on sea level pressure is detectable only in the tropical and subtropical region. This region has experienced increases in SLP through most of the year and at most latitudes, consistent with simulated increases in SLP. While these simulated and observed increases in SLP are smaller in magnitude than the large decreases observed at high latitudes, the internal variability is also lower in the tropics and subtropics. The impacts of SLP trends on other climate variables have mainly been examined in the context of the annular mode impacts at mid and high latitudes [e.g., *Thompson et al.*, 2000; *Gillett et al.*, 2006]: Our results suggest the anthropogenically-forced low-latitude SLP trends are larger relative to internal variability, and their regional climate impacts could therefore also be important. The mechanisms responsible for these tropical mean increases in SLP remain to be investigated: Increases in tropical water vapour could be a contributor [*Trenberth et al.*, 2007].

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